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Tension grips the flow

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Surface tension plays a dominant role in the formation and stability of soap films. It renders them both a quasi two-dimensional fluid and an elastic membrane at the same time. The techniques for measuring the surface tension of the soap solution may very well apply to the static soap film, but how can the surface tension of a soap film be unintrusively measured, and what value would it assume? The answer being at the intersection of physical chemistry, non-equilibrium physics, and interfacial fluid dynamics, is not amenable to deduction *via* established methods. In a joint theoretical and experimental study, Sane et al. (*J. Fluid Mech.* vol. *xxx*, *yyy*) exploit elasticity theory to glean the answer through a simple, yet elegant framework.

Keywords. Soap films, Surface Tension, Gibbs elasticity.

1. Introduction

The earliest observations of capillary action, at least within occidental records, are traced to Leonardo da Vinci da Vinci(1452-1519), Maxwell & Strutt(1911) and Galileo's student Niccoló Aggiunti Nelli(1759). The first measurements by Francis Hauksbee Hauksbee(1709) were expanded upon by James Jurin resulting in Jurin's law Jurin(1718), Jurin(1719). The formal introduction of *Surface Tension* by Johann Andreas von Segner Segner(1751) paved the way for establishing the theoretical foundations of interfacial science with the Young-Laplace equation Young(1805), Laplace(1806). The three century delay from the first observations by Leonardo (1452 - 1519) to the Young-Laplace equation was neither for lack of effort nor ingenuity, but for the fact that in spite of the simplicity of its basis, interfacial science is notorious for its misunderstandings and interpretational difficulties. Even Young and Laplace succumbed to such obscurities Maxwell(1878) until Carl Friedrich Gauss unified their approaches Gauss(1830); such difficulties were not limited to theory alone but plagued experiments alike. For instance, easy contamination of water surface rendered reliable experimental determination of surface tension nearly impossible until development of the Pöckels scale Pöckels(1891). All these advances concerned static interfaces where the equilibrium shape or geometry of the surface took centerstage.

An understanding of the Marangoni stress arising from gradients of surface tension arose along a similarly convoluted path. Although interfacial dynamics of self-propelled camphor particles were reported by late 17th century Heyde(1686) and investigated by some brilliant minds (Tomlinson(1869) provides a historical review), the phenomenon was explained as arising from surface tension gradients only two centuries hence Van der Mensbrugghe(1869). Mistaken hypotheses percolating along the way had to be painstakingly disproven before the correct explanation could emerge; yet another example of difficulties that beset this field. The Marangoni effect – mass transfer along a fluid interface due to surface tension gradient – was only identified in 1855 by James Thomson,

brother of Lord Kelvin Thomson(1855), explained 14 years later by Carlo Marangoni Marangoni(1869), and eventually received complete theoretical treatment with the Gibbs adsorption isotherm Gibbs(1878).

Soap films hold especial significance in interfacial science owing to them being the prototypical instance of surface tension dominated effects. Much like the development of interfacial science, static soap film behaviour, e.g. minimal surfaces and related geometric properties Plateau(1873), Dewar *et al.*(1927)Dewar, Ross & Dickson formed the focus of early studies and soap film dynamics were rarely studied Mysels(1959). Soap film hydrodynamics Couder *et al.*(1989)Couder, Chomaz & Rabaud, Chomaz(2001) as a study in and of itself is relatively recent and has rapidly gained footing as a standard experimental tool in the investigation of two-dimensional hydrodynamics, including turbulence Kellay & Goldburg(2002), vortex dynamics Roushan & Wu(2005), and fluid-structure interactions Zhang *et al.*(2000)Zhang, Childress, Libchaber & Shelley. Unlike early works, both the three-dimensional character of soap films and the effect of surface tension have become prominent in recent studies Tran *et al.*(2009)Tran, Chakraborty, Gioia, Steers & Goldburg, Gilet & Bush(2009), thus prompting the question, “*What is the surface tension of a flowing soap film?*”

2. Overview

The article by Sane *et al* Sane *et al.*(2018)Sane, Mandre & Kim addresses precisely this question both theoretically and experimentally. The question assumes significance in the first place because it is the surfactant that imparts stability to the soap film. The surfactant molecules populate the interface and the bulk fluid. In equilibrium, the molecules are distributed in the two phases according to the adsorption isotherm, and the surface tension of the soap film is reduced below that of pure water by the adsorbed surfactant. Upon stretching the film, bulk molecules are transferred to the freshly created surface, a process whose duration is dictated by surfactant transport and sorption kinetics. For a soap film constantly flowing under external pumping of solution, it is not clear how the time scale of the hydrodynamics that deform the interface compares with the surfactant equilibration time scales. The film’s surface tension could vary with the flow regime thereby necessitating its experimental determination. Such a measurement probes the extent to which the surfactant dynamics are out of equilibrium.

Unfortunately, standard surface tension measurement techniques fail here. For instance, the pendant drop method requires bulk fluid and is therefore disqualified by default whereas other techniques such as the Du Noüy and Wilhelmy plate methods are invasive and become especially problematic if the film flow speed exceeds the Marangoni wave speed Kim & Mandre(2017). Sane *et al* Sane *et al.*(2018)Sane, Mandre & Kim circumvent all these difficulties by imaginatively exploiting the Euler-Bernoulli equation to relate the bending curvature of wires that bound the flowing film to its surface tension. Standard gravity-driven soap films employ two nylon wires held in tension by a hanging mass of known weight, and the soap solution is drained down the wires under gravity. When the nylon wires are pulled apart, a soap film is created between the wires and the solution now flows down the film. But the film’s surface tension which tries to minimize its surface area exerts a force that tries to pull the nylon wires back together and imparts curvature to them while in tension (please see title image). By measuring the bending curvature of the nylon wire against applied tension yields the surface tension of the film in flow.

Sane *et al* Sane *et al.*(2018)Sane, Mandre & Kim have measured the surface tension of flowing soap films under different film thicknesses and soap concentrations and found

an apparent equivalence between surfactant dilution and thinning of the soap film. Since the film's surface tension depends upon surfactant concentration at the interface, this translates to the fact that thinner films possess higher surface tension. Relating the film thickness and surfactant concentration through surfactant conservation, they develop a quantitative model based on Langmuir's adsorption isotherm. This model finds confirmation when surface tension measured at different values of the solution flux and at different concentrations collapses onto a master curve. This observation also explains that the soap film's Marangoni elasticity measured using the angle of oblique Marangoni shocks (see title Figure) does not vary with the film width, flow rate and soap concentration because the interface is saturated with soap (see Kim & Mandre(2017)).

3. Outlook

In the process of determining the surface tension of flowing soap films, Sane *et al* Sane *et al.*(2018)Sane, Mandre & Kim have also discovered a heretofore unknown dependence of the soap film's terminal velocity on the film thickness and its flux. Standard two-dimensional hydrodynamics assumes the terminal velocity arises from air drag, which is expected to be substantial on account of the large exposed area of the film to surrounding air, and is usually modeled as a linear drag term in the two-dimensional Navier-Stokes equation. The additional dependence on film thickness and flux points to a gaping hole in our understanding and one hazards to proffer the informed opinion that there is most probably new physics in two-dimensional hydrodynamics.

Furthermore, commercial detergents employed in soap film experiments are complex formulations comprised of different surfactants. The proof of principle presented by Sane *et al* begs careful characterization against pure surfactants not just for surface tension measurement, but more importantly to gain better understanding of stationary state sorption kinetics. This point applies beyond soap films to the general problem of surfactant transport. Surfactants dissolve to varying degrees in bulk fluid and can be transported either in the adsorbed (at the interface) or in bulk phase. Simultaneous measurement of surface and bulk surfactant concentrations, Marangoni stresses and surface rheology, sorption kinetics, and how these quantities are correlated together is an experimentally formidable task Langevin & Monroy(2014), Elfring *et al.*(2016)Elfring, Leal & Squires, Mandre(2017), Bandi *et al.*(2017)Bandi, Akella, Singh, Singh & Mandre and contains all hallmarks of the obscurities faced by interfacial science since its inception. It is in this context the work of Sane *et al* Sane *et al.*(2018)Sane, Mandre & Kim bears hope that perhaps a *renaissance* is afoot in interfacial science, prompting one to close with the famous quote by Leonardo da Vinci, the discoverer of capillary action, "*che non terminano in nota experientia*".

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